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Conduction mode - Broadening the range of applications for laser welding

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Abstract

Conduction laser welding opens up a range of innovative applications for laser welding. This relatively novel mode of laser processing expands the application potential significantly beyond what is normally achieved today. The main reason for this could be attributed to the different characteristics of conduction process when compared to keyhole laser welding. An example is the higher stability of conduction which results in welds of higher quality and better control of the welding process. Despite the advantages of conduction laser welding, it is yet to be exploited significantly for industrial applications and there are very few applications for which this mode of operation is used. This paper is aimed at presenting different varieties of applications for conduction laser welding using a fibre laser. This ranges from high quality aluminium welds to laser brazing of stainless steel to metal foams. The objective of this paper is to highlight the main features of conduction laser welding process and exemplify some conduction laser welding applications.

Keywords: *Conduction mode, laser welding*

1. Introduction

Laser welding depending on the processing conditions has broadly two different operational regimes conduction and keyhole welding. The beneficial characteristics of keyhole welding, especially large penetration depth and relatively small heat affected zone attracted more industrial applications. However, keyhole welding also presents several problems that may lead to high levels of porosities and other weld defects [1-3]. In keyhole mode welding most of the beam is absorbed which may be disadvantageous when welding high reflectivity materials (e.g. aluminium). This is due to the fact that much power is needed to start the keyhole but as soon as it starts the absorptivity jumps from 3% to 98% which may cause damage to the welded structure [4].

On the other hand, conduction laser welding has been slightly neglected by industry despite several advantages. Conduction welding can be a viable alternative to keyhole welding mainly due to the fact that it is a very stable process and easier to obtain high quality welds free of pores and spatter [5]. Conduction mode of welding occurs when the vaporisation of the material is insignificant, in other words, when the thermal intensity is not high enough to cause boiling [6]. Conduction laser welding can also be achieved with significantly low laser cost, because it does not require a high beam quality or a very high power [7]. The following text will present examples of some of the applications of conduction mode laser welding.

One of the main applications of conduction laser welding is welding aluminium alloys. The high strength to weight ratio of aluminium made it a preferred choice for structural applications in the transportation and aerospace sector[8]. The welds obtained using keyhole laser welding in aluminium have tendency to form porosity and weld metal cracking. Normally the porosity presented is associated to gas entrapment during solidification and vaporisation of elements with low boiling point[9]. Another issue of keyhole welding is formation of solidification cracking, mainly at high welding speeds[10]. In order to overcome these issues in laser welding some studies on welding of aluminium were carried out using conduction mode. Using this mode it was possible to obtain welds with no porosity or cracking [5, 9, 11]. Conduction laser welding also presents better mechanical properties when compared to keyhole laser welding due to the loss of elements and due to the fast cooling rates obtained in keyhole [5].

Another application of conduction laser welding is in joining of dissimilar materials [12]. The use of dissimilar materials in the automotive and aircraft industry has initiated several researches in trying to join different materials like aluminium to steel. Due to the difficulty of this type of welding several studies using resistance spot welding [13, 14],arc welding [15, 16], brazing [17] and Friction Stir Welding [18, 19] have been made. However, in recent years laser welding has been introduced as an alternative for welding steel to aluminium. Studies using keyhole welding in order to join aluminium to steel were made [20] but with limited success. Nevertheless, studies using conduction laser welding have shown very good results [21-23]. The advantage of using conduction laser

welding in this application is related to the stability of the process that allows a better control of the temperature in the interaction area between the aluminium and the steel [22].
Conduction laser mode is also used in laser cladding for surface treatment and repair. The use of this laser mode allows a more accurate and precise way of repairing components. Due to a better control of the heat cycle it is possible to produce functionally gradient materials and graded coatings [24, 25].
The present works aims at presenting several applications of conduction laser welding and how this process can be adopted with other fusion welding process e.g. TIG or MIG originating hybrid conduction weld. In this paper some examples of conduction laser welds carried out at the Welding Engineering Research Centre (WERC), Cranfield University were presented and analyzed in terms of its suitability for different critical applications.

2. Experimental Procedure

The welds presented in this paper were made using an IPGYLR-8000 Fibre laser with a maximum power of 8000 W and a wavelength of 1070 nm. The system consists of a feeding fibre of 200 µm and a process fibre of 300 µm. During these experiments the optical setup used was a 125 mm collimating lens and a 500 mm focusing lens. Parameters like power used, beam diameter and welding speed were adjusted according to the application studied. In order to obtain different beam diameters a defocused laser beam was used. Each application has a specific experimental setup which will be explained in the relevant sections chapter.

3. Applications

In the following chapters some applications of conduction laser welding are presented.

3.1 Aluminium laser welding in conduction mode

The material used was 12 mm thick aluminium alloy 2024. The chemical composition of this alloy is presented in Table 1. The surface of the aluminium was wire brushed and then coated with graphite in order to help the coupling of the laser beam to the material. In order to obtain the 5.25 mm beam diameter the laser beam was defocused. The welds obtained in this experiments were evaluated in terms of weld zone profile, porosity and cracking which are the most common defects when laser welding aluminium.

Table 1 - Chemical composition of Aluminium alloy 2024

Element (wt%) 2024 – T3									
Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Others
90.7-94.7	Max 0.1	3.8 – 4.9	Max 0.5	1.2 – 1.8	0.3 – 0.9	Max 0.5	Max 0.15	Max 0.25	0.15

Figure 1 and Figure 2 show one of the welds obtained using conduction laser welding of aluminium. The parameters used in this experiment were a power of 4.5 kW, a welding speed of 0.6 m/min and a beam diameter of 5.25 mm.

Figure 1 - Metallographic image of the weld bead

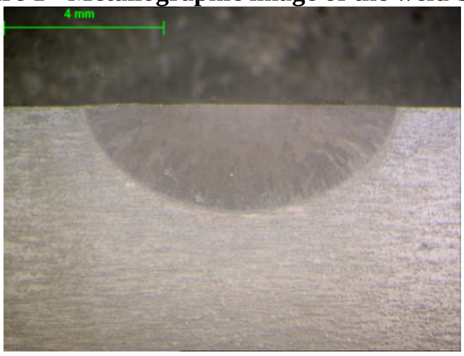
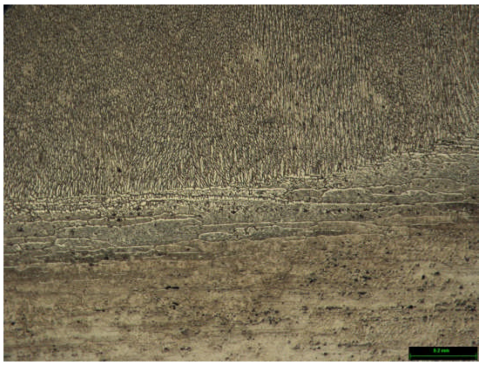


Figure 2 - Micrograph of the melted area and heat affected zone of the weld



Evaluating Figure 1 and Figure 2 it is possible to see that the common defects associated to laser welding of aluminium, like porosity and cracking, are not present. The weld bead profile also presents a very flat top surface. The main advantage of this mode during welding of aluminium alloys is no vaporization which is one of the main causes of porosity. Other advantage is the slow cooling that improves the weld bead geometry.

3.2 High quality low carbon steel welds

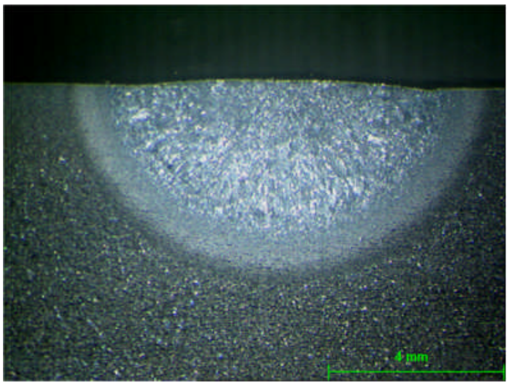
Tests were made in 12 mm plates of S275 mild steel in order to evaluate the welds obtained when using conduction mode. Table 2 presents the chemical composition of the S275 mild steel. The surface of the plate was wire brushed and then cleaned with acetone. In order to obtain the 5 mm beam diameter the laser beam was defocused. PureShield Argon was used as shielding gas with a flow rate of 10 l/min.

Table 2 - Chemical composition of S275 mild steel

Element (wt%) S275 mild steel				
C	Mn	Si	P	Fe
0.25	1.60	0.50	0.05	Balance

During welding no spatter was observed. The absence of spatter is also related to the fact that in conduction mode there is no vaporization, which causes spatter.

Figure 3 - Macro-profile of a conduction weld in S275 mild steel



The weld in Figure 3 was obtained using 7kW of power, a beam diameter of 5 mm and a welding speed of 0.3 m/min. The results emphasise one of the main characteristics of conduction welding, which is the stability of the process, noticeable. This also results into good surface appearance. The fact that during welding no spatter occurs explains why using this process it is possible to obtain a weld profile with no undercut and porosity.

3.3 Joining Aluminium to steel

In this experiment the materials used were AA2024 (composition shown in Table 1) and a low ferritic carbon steel, the composition is shown in Table 3.

Table 3 - Chemical composition of Low carbon Steel

Element (wt%) Low Carbon Steel								
C	Si	Mn	P	S	Cr	Ni	Cu	Fe
0.15	0.17	0.52	0.019	0.021	0.1	0.1	0.1	Balance

Complete overlap welds were made using steel on top and the aluminium on the bottom. This configuration gives better weld quality mainly due to the thermal characteristics of both materials. The thermal conductivity of aluminium being higher than that of steel, when aluminium is used on top it results into a much larger interfacial area. This is because the heat tends to flow along the interface in the aluminium part rather than heating the steel. When steel was used on top the thermal conductivity of the two materials allow a better conduction of heat from the steel to the aluminium.

Figure 4 - Micrograph of the interface between aluminium and steel

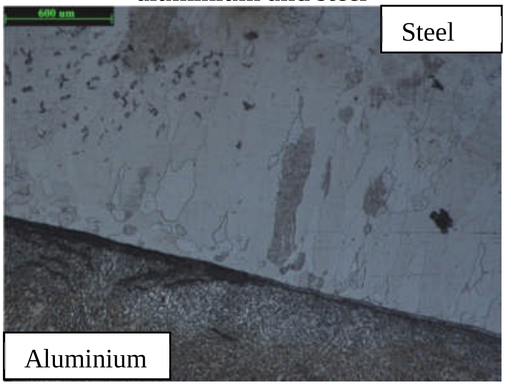
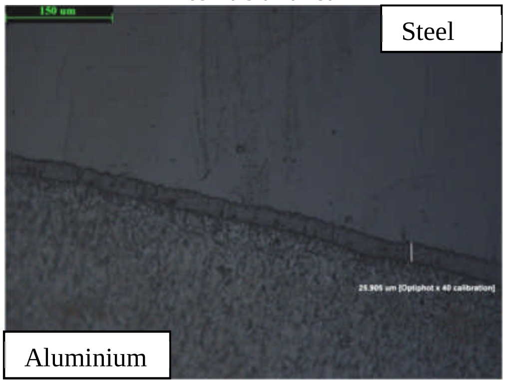


Figure 5 - Micrograph with higher magnification of the interfacial area



The parameters used in the weld presented in Figure 4 and Figure 5 were a Laser power of 4 kW, a beam diameter of 13 mm and a welding speed of 0.5 m/min. There was no defect on the joint area between steel and aluminium including the interfacial area. It is possible to see that there is a thin layer of intermetallics formed due to interfacial reaction between the two materials. The mechanical properties of the joint were found not to be affected by this thin intermetallic layer.

Welding aluminium to steel is very difficult to implement. The use of conduction laser welding allows a better control of the heat delivered to the work piece. In order words by using this laser welding mode it is possible to control the melting of both materials, which for this specific application is of great importance. The main idea is to conduct the heat generated by the laser beam through the steel without melting the steel or by just having very small amount of melted material and melt the aluminium underneath.

3.4 Laser brazing of stainless steel to metal foams

In this experiment two different varieties of metallic materials were used. The first one was 304L Stainless steel, the composition of this material is presented in Table 4. The other material was nickel-chromium metal foam in two different grades. The grades used were the 1116 grade with maximum of 16 pores per sq- inch and the 3743 grade with a maximum of 43 pores per sq- inch. Both the foams used were 5 mm thick .

Table 4 - Chemical composition of 304L Stainless Steel

Element (wt%) 304L Stainless Steel								
C	Mn	Si	Ph	Ag	Cr	Ni	N	Fe
0.03	2.0	0.75	0.045	0.03	14.0	12.0	0.1	Balance

The welding operation was carried out in lap configuration with the stainless steel on top of the metal foam. In order to have a proper coupling with the laser the stainless steel was coated with graphite. In the junction of the two materials Silver braze foil was used. The composition of the brazing foil is presented in Table 5.

Table 5 - Chemical composition of the brazing foil

Element (wt%) Brazing Foil			
Ag	Cu	Zn	Cd
40.0	19.0	20.0	20.0

The principle of this application was the use of conduction mode in order to conduct the heat using the stainless steel allowing the foil to be melted which will then wet both the surfaces to form the joint The final results, shown in Figure 6 and Figure 7, where obtained using a 15 mm beam diameter, 0.3 m/min welding speed and a power of 1.4 kW.

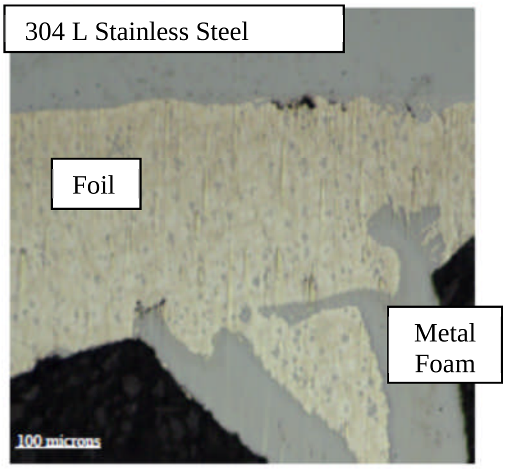


Figure 6 - Micrograph of laser braze joint of stainless steel to 1116 Grade foam

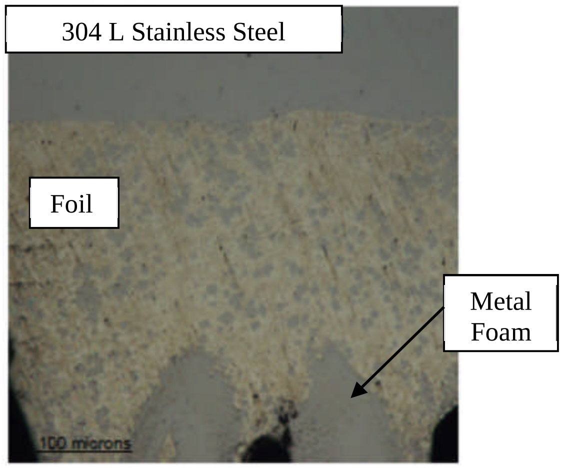


Figure 7 - Micrograph of laser braze joint of stainless steel to 3743 Grade foam

The use of conduction mode in laser brazing showed significant advantages. When compared to other processes fusion welding processes e.g.TIG, MIG and torch brazing conduction mode laser brazing has the advantage of higher productivity. In terms of the overall quality of the joint, laser brazing showed very good results. Vacuum brazing is the only other technique that can produce equivalent or superior joints as compared to laser conduction brazing. However, this process can be applied to samples of any size while in vacuum brazing the size is limited by the size of the vacuum furnace. This application highlights another property of conduction mode which is the stability of the process that allows a better control of the heat along the work piece. To summarize laser brazing in conduction mode presented not only very good results but also as process with high productivity, flexibility and stability.

3.5 Laser-Arc hybrid conduction welding

The material used in this part of the paper was 1.6 mm thick plates of aluminium alloy 2024; the composition of this material is presented in Table 1. All the welds were made in butt joint configuration. The surface of the aluminium was wire brushed and cleaned with acetone. The 5 mm beam diameter was obtained by defocusing the laser beam. The TIG power supply used was a Migatronic BDH 440 Commander with an electrode of 3.2 mm diameter. In this experiment AC TIG mode was used with 70% cleaning during the positive half cycle in order to pre clean the surface and reduce the top surface oxidation. PureShield Argon was used as the protective shielding gas and also as trailing and back shielding. The filler wire used was 1.2 mm diameter 2139 which has a composition of aluminium and 6% of copper. The wire was fed perpendicular to the welding direction. In order to control distortion a vacuum fixture was used.

The idea of using TIG in order to assist conduction mode welding of aluminium is to prevent reflection of the laser beam by aluminium workpiece. The TIG process will pre-melt the surface of the aluminium allowing a better coupling by the laser beam avoiding the use of graphite on the surface of the aluminium. In order to achieve this, trials were taken with the TIG torch leading and the laser beam trailing.

Figure 8 and Figure 9 present an example of a weld obtained using hybrid laser in conduction mode plus TIG welding process. In this sample the parameters used were the following, 2 kW of laser Power, a Beam Diameter of 5 mm, TIG current of 80 A, wire feed speed of 2.3 m/min and a welding speed of 1 m/min.

Figure 8 - Macrograph of the TIG plus laser in conduction mode weld

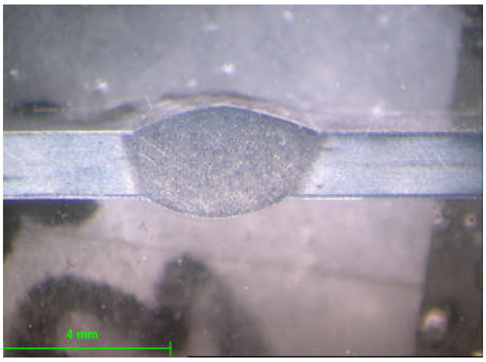
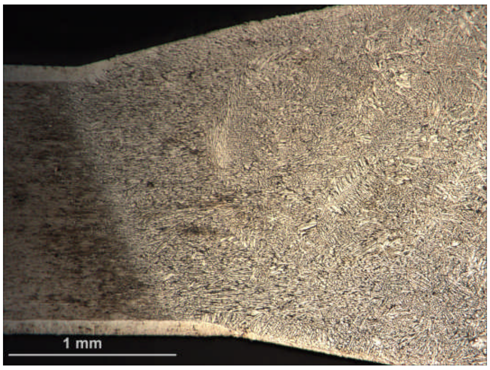


Figure 9 - Micrograph of the TIG plus laser in conduction mode weld



Based on Figure 8 and Figure 9 it is possible to see that by using the welding process it is possible to obtain extremely high quality welds, with no porosity, cracks, undercut or spatter. Also the use of a hybrid process solves the problem of reflection of the laser beam when welding aluminium alloys in conduction mode without the use of surface treatment to help absorption.

4. Conclusion

The use of conduction laser welding described in this paper show a whole range of possibilities for advanced and critical joining applications. Laser conduction mode of welding was shown to be extremely applicable where high quality and stable welds are required. The fact that in conduction mode there is hardly any vaporisation of elements, defects like porosity, excessive spatter, undercut etc. are eliminated improving the overall aspect and properties of the weld bead. Larger beam diameter used in conduction mode allows a bigger fit up tolerance. Normally conduction laser welding is associated to the welding of aluminium; although the whole range of applications is yet to be fully explored.

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